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# Compression behaviour of minerogenic low energy intertidal sediments

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## Abstract

Existing geotechnical approaches that describe volumetric changes in intertidal sediments in response to applied vertical effective stresses are limited by a lack of empirical research into their one-dimensional compression behaviour. In this paper we address this deficiency by presenting the results of an investigation into the compression behaviour of minerogenic low marsh and tidal flat sediments. We have tested samples of these sediment types obtained from Greatham Creek (Cowpen Marsh, Tees Estuary, UK). Analysis of physical properties and oedometer compression tests demonstrates that, contrary to the implicit assumptions of existing models, the surface sediments studied are overconsolidated. Structural variability between samples arises due to sedimentological factors, notably variations in organic content. We attribute overconsolidation to tidal exposure and falls in groundwater level that cause desiccation and capillary suction stresses. Greater rates of compression with respect to effective stress occur

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in sediments with higher initial voids ratios and more open, unstable initial structures. Variability in structure decreases with application of higher effective stresses due to the destructuration of the sediments, which also creates increased homogeneity of compression behaviour under higher effective stresses. We subsequently develop a new conceptual framework to describe compression behaviour in minerogenic intertidal sediments that incorporates overconsolidation. We advocate a statistical approach that accounts for structural variability and variations in compression behaviour at effective stresses less than and greater than the yield stress. We argue that our conceptual framework is broadly applicable to minerogenic intertidal sediments at different locations and burial depths within Holocene stratigraphic sequences providing site-specific compression data are collected. Inter-site transfer and application of measured material properties should not be undertaken due to local variations in compression behaviour resulting from varying ecological, sedimentological, geochemical, climatic, geomorphic and hydrographic conditions. The individual characteristics of different field locations should be carefully considered before the suggested framework is routinely applied.

**Keywords:** Autocompaction; compression; intertidal sediments; salt marsh; mudflat; sea level.

## **1. Introduction and Aim**

Autocompaction describes an interlinked group of syn- and post-depositional diagenetic processes that result in volumetric reductions of sediments (Allen, 2000). Autocompaction is a key geomorphic process in low energy intertidal environments, lowering the elevation of the land surface relative to the intertidal frame (Kaye and Barghoorn, 1964; Cahoon *et al.*, 1995). Conceptual and exploratory numerical models (Allen, 1999) and observational (e.g. Cahoon *et al.*, 1995; Cahoon *et al.*, 2000) and stratigraphic (e.g. Long *et al.*, 2006; Törnqvist *et al.*, 2007)

data highlight the importance of autocompaction processes. The increased rates of relative sea level (RSL) that result from autocompaction can contribute to degradation and erosion of these biogeomorphologically sensitive environments (Reed, 1990; 1995; French and Spencer, 1993; Day and Giosan, 2008) and an associated loss of valuable wetlands (Knutson, 1998; Spurgeon, 1999; Hughes, 2004; French, 2006; Wamsley *et al.*, 2010).

Autocompaction complicates attempts to quantify past sea level changes obtained from intertidal sedimentary sequences by lowering sea level index points from the original altitudes at which they were deposited (Allen, 2000; Shennan and Horton, 2002; Edwards, 2006; Long *et al.*, 2006; Horton and Shennan, 2009). Without correction for autocompaction, the rate and magnitude of inferred sea level rises can be overestimated (Shennan *et al.*, 2000). Any subsequent practical applications of geological sea level data obtained from intertidal sediments, such as for the analysis of causal relationships between climate, ice sheet behaviour, neotectonics and sea level (Wake *et al.* 2006; Shennan *et al.*, 2009; Teferle *et al.* 2009; Engelhart *et al.*, 2009), the detection of anthropogenic impacts on the rate of sea level rise (Donnelly *et al.*, 2004; Gehrels *et al.*, 2005; Kemp *et al.*, 2009), and calibration and refinement of geophysical models (Peltier *et al.*, 2002; Brooks *et al.*, 2008), are confounded by this error.

The rate of autocompaction varies in response to imposed stress conditions that are controlled by sedimentation rates and initial sediment bulk density (Tovey and Paul, 2002), and the type, thicknesses and configuration of over- and under-lying lithologies (Allen, 1999; Edwards, 2006; Long *et al.*, 2006; Horton and Shennan, 2009; van Asselen *et al.*, 2010). Due to the interaction of these factors, cumulative autocompaction rates within a stratigraphic column are typically non-linear. Average rates cannot simply be extrapolated through time and across

space without a process-based understanding of autocompaction and the volumetric response of the particular sediments under consideration.

Predictive models of autocompaction are of potential value for the modelling of future and historic elevation changes in intertidal sediments. However, little research has been undertaken to quantify the autocompaction mechanisms in response to different controlling variables. Conceptual and numerical autocompaction modelling frameworks developed for use in classical civil engineering (e.g. Been and Sills, 1981), petroleum geology (e.g. Audet and Fowler, 1992) or subtidal marine geology (e.g. Skempton, 1970) are not directly applicable to low energy intertidal sediments due to differences in the environmental and stress conditions and the timescale(s) of interest.

In this paper we start to address the limited understanding of autocompaction behaviour in low stress, low energy intertidal environments. We target minerogenic (< 50 % organic matter by dry mass) sediments and the effects of mechanical compression processes. Quantifying the effects of biological decay is beyond the remit of this study, but the sediments studied are broadly typical of the predominantly minerogenic deposits that accumulate in intertidal and salt marsh environments on NW European coasts (Allen, 2000). The aim of this paper is to develop our understanding of the compression behaviour of minerogenic low energy intertidal sediments. In order to achieve this aim, we have the following objectives:

1. To present results of field monitoring and laboratory testing programs designed to characterise the intertidal depositional environment and the relevant geotechnical characteristics of the materials that form there;
2. To use these data to examine whether the assumptions of an existing, previously-used mechanical autocompaction model are valid; and

3. To develop a conceptual framework that describes and explains mechanical autocompaction behaviour in minerogenic intertidal sediments; and to consider the spatial and temporal transferability of the framework.

## **2. Autocompaction Models in Low Energy Intertidal Sediments**

Autocompaction models seek to describe volumetric and elevation changes in sediments caused by decreases in pore space (increases in density) (Boudreau and Bennett, 1999), structural collapse (Delaune *et al.*, 1994) or biological decay and chemical alteration of organic matter (Clymo, 1965; Lillebø *et al.*, 1999) (see van Asselen *et al.*, 2009).

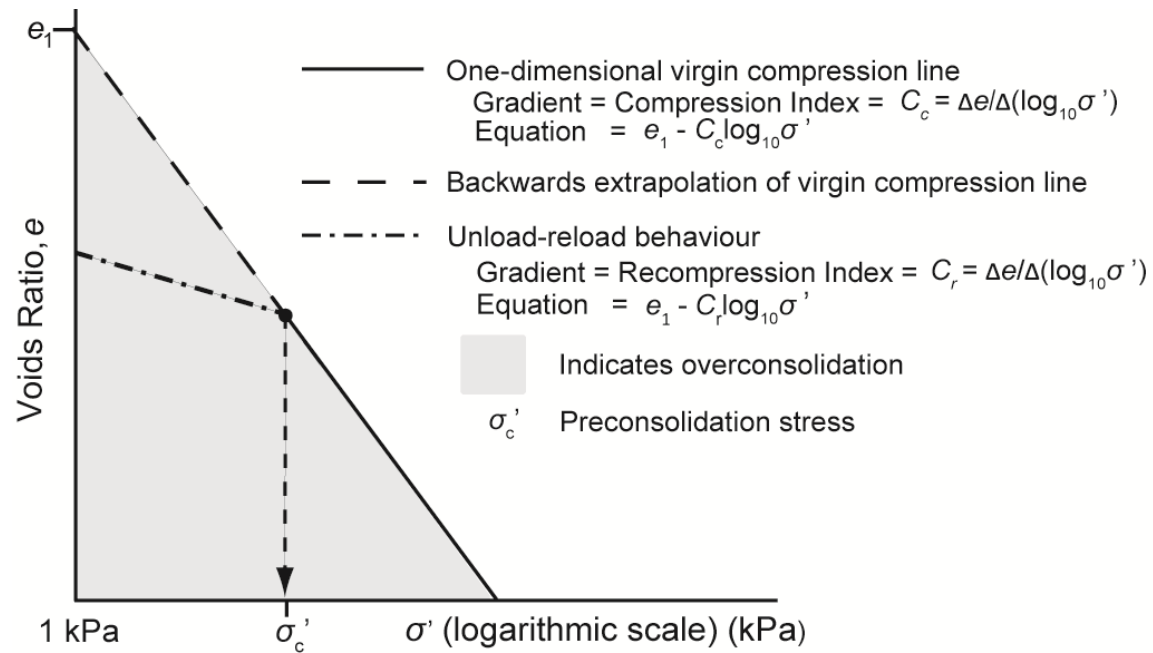
Whilst progress has been made into the effects of microbiological and oxidation processes on peat decay (e.g Hackey and de la Cruz, 1980; Blum, 1993; Conn and Day, 1997; Latter *et al.*, 1998; Charman, 2002; Gambolati *et al.*, 2006), the complex operation and strong time-dependency of these non-mechanical diagenetic processes and the spatial and lithological variation therein has limited the development of quantitative models of biologically- and chemically-effected volumetric change. In contrast, mechanical autocompaction (compression) models are more common (e.g. Pizzuto and Schwendt, 1997; Paul and Barras, 1998; Tovey and Paul, 2002) since the relationship between the vertical stress (pressure) exerted by the deposition of sediments and the density and volume of underlying materials can be better quantified. Crucially, the validity of these models depends on an empirically-informed understanding of mechanical autocompaction behaviour and quantification of volume changes.

The autocompaction model used most frequently in UK intertidal stratigraphic settings is the One-Dimensional Virgin Compression Law (termed Terzaghi's Compression Law by Massey *et al.*, 2006), or variations thereof (e.g. Paul and Barras, 1998; Massey *et al.*, 2006). Such virgin compression models (VCMs) describe the volumetric state of sediments by the height of the

sedimentary column or the voids ratio ( $e$ ), a dimensionless volumetric parameter defined as the ratio of the volume of voids to the volume of solid particles (Powrie, 2004). A key assumption is the inverse relationship that is assumed to exist between volume or  $e$  and the common logarithm of vertical effective stress ( $\sigma'$ ), defined as

$$\sigma' = \sigma - u \quad (1)$$

where  $\sigma$  is the total stress resulting from the combined weight of the overlying sediments, and  $u$  is pore water pressure (Powrie, 2004). On a plot of  $e$  against  $\sigma'$  (common logarithmic scale), this relationship plots as a straight line of negative gradient. The full volumetric behaviour of sediments is typically modelled through ‘backwards’ extrapolation of the virgin compression line to the intercept (i.e. 1 kPa) on the basis of *in situ* properties (Figure 1) (Smith, 1985; Paul and Barras, 1998; Tovey and Paul, 2002; Massey *et al.*, 2006).



**Figure 1** Key components of compression models in  $e \log \sigma'$  space.



Virgin compression models are popular for two reasons. Firstly, VCMs are simple to apply as they require only two geotechnical input parameters: the compression index,  $C_c$ , and  $e_1$ , the voids ratio encountered at the depositional surface (1 kPa on a logarithmic effective stress scale). The compression index can be measured directly from oedometer testing or estimated from correlations with index properties, notably the liquid limit (Paul and Barras, 1998, after Skempton, 1944). Secondly, the model has been shown to be a good approximation of the volumetric behaviour of natural *in situ* sediments (Skempton, 1970; Burland, 1990) that have not experienced an effective stress greater than that exerted by the current overburden. Such soils are described as normally consolidated and their volumetric states can be described by the virgin compression line in  $e \log \sigma'$  space (Figure 1). Virgin compression models are based on two key assumptions. The first assumption is that the stratigraphic units studied are lithologically uniform with no variability in structure (voids ratio) at a specified effective stress, and display no variability in compression behaviour in response to applied effective stress.

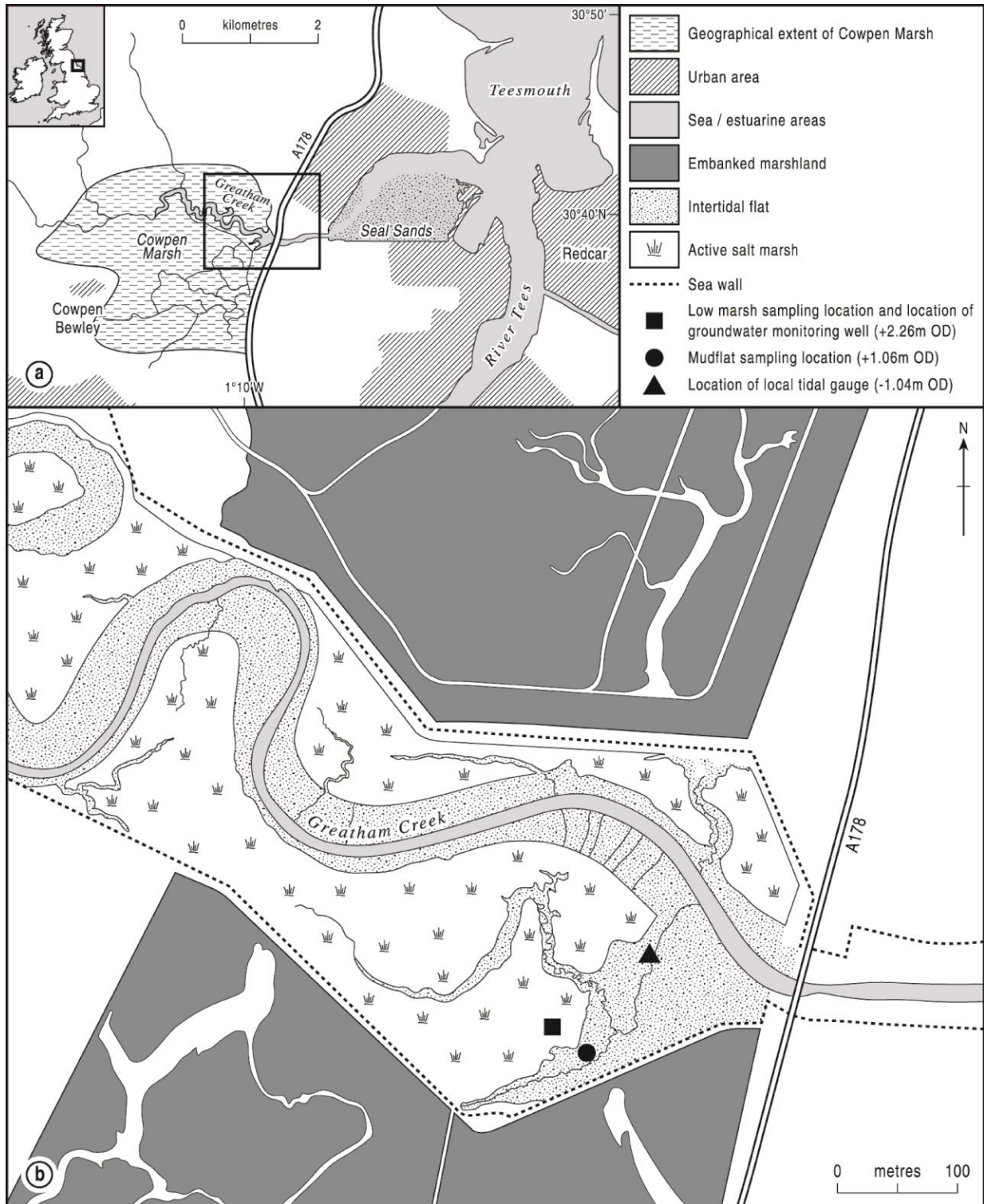
The second assumption is that the sediments are normally consolidated as a result of overburden loading and no other processes. If processes other than overburden loading contribute to either effective stress increase, or result in bulk density increases without increases in effective stress, the sediments will be overconsolidated – that is, the sediment structure (voids ratio) would reflect previous exposure to an effective stress that is greater than the current overburden. Such soil structures plot below the virgin compression line in  $e \log \sigma'$  space, indicated by the grey shaded area in Figure 1. Overconsolidated sediments are more resistant to effective stress increases until the previous maximum effective stress (termed the preconsolidation stress) is exceeded. Overconsolidated sediments follow a compression line in  $e \log \sigma'$  space of decreased gradient, described by the recompression index ( $C_r$ ) (Figure 1). If

overconsolidation occurs at the depositional surface as a result of processes other than those resulting from overburden deposition, the virgin compression line will not accurately describe volume changes at effective stresses less than the previous maximum value of effective stress experienced by the sediment. This would contravene a key condition of VCMs, thereby questioning the accuracy of any research that uses VCMs to account for volumetric change.

### **3. Field Site**

The study site is the northeastern corner of Cowpen Marsh in the Tees Estuary (Figure 2). The site is connected *via* Greatham Creek to Seal Sands and the North Sea. The tidal range is 6.1 m (spring tidal range of 4.6 m) (Admiralty Tide Tables, 2005). The site comprises a small salt marsh platform adjacent to tidal mudflats that fringe the main tidal creek (Table 1). The distribution of sediment and floral zones (Table 1) is linked to elevation with respect to the tidal frame and conforms to Allen's (2000) generalised lithofacies model of late Holocene coastal sediments of NW Europe.

Cowpen Marsh has been a Site of Special Scientific Interest since 1966 (Natural England, 2009). Hence, public access to the active intertidal zone is restricted and livestock grazing does not take place within the active marshland. This minimises potential disturbance to the sediments.



**Figure 2** Study site location. Boxed area in (a) (regional context) is displayed in (b) (local scale plan showing sampling locations).

**Table 1** Description of contemporary vegetation at Greatham Creek and its zonation by altitude and elevation above mean sea level. Altitude and elevation ranges are based on point estimates; boundaries between different zones are transitional, occurring over a 0.1 – 0.3 m elevation range. A variable 0.2 – 0.3 m cliff marks the transition between mudflat and salt marsh zones.

Floral zone	Vegetation	Approximate altitudinal range (m OD)	Elevation range (m above mean sea level)
Mudflat	Minerogenic mudflat substrate with no <i>in situ</i> growth of vascular plant species.	0.34 to 1.77	0.00 to 1.42
Upper tidal flat/ pioneer marsh zone	Mudflat substrate covered by a thin algal mat, with a scattered presence of <i>Salicornia europea</i> (1 - 5% coverage).	1.89 to 1.92	1.54 to 1.57
Low marsh	100 % coverage of substrate dominated by <i>Puccinellia maritima</i> (c. 50%) and <i>Salicornia europea</i> (c. 40%), with occasional <i>Aster tripolium</i> , <i>Limonium vulgare</i> , <i>Sueda maritima</i> , <i>Spergularia</i> , and <i>Plantago maritima</i> .	2.20 to 2.31	1.85 to 1.96
Mid marsh	100 % of substrate characterised by an increase in the dominance of <i>Sueda maritima</i> , <i>Aster tripolium</i> and <i>Limonium vulgare</i> and a corresponding decrease in <i>Puccinellia maritima</i> . Increased species diversity at towards transition to high marsh, namely <i>Festuca rubra</i> and <i>Festuca ovina</i> .	2.31 to 2.49	1.96 to 2.14
High marsh	100 % coverage of substrate dominated by <i>Elymus pycnanthus</i> accompanied by <i>Festuca rubra</i> , <i>Festuca ovina</i> , and <i>Limonium vulgare</i> .	2.49 to 3.25	2.14 to 2.90

#### 4. Methods

We undertook a combined environmental monitoring and geotechnical laboratory testing program to test the assumptions outlined in Section 2. First, we installed a self-logging pressure transducer at -1.04 m OD to record variations in tidal water depths at 5 minute intervals. This enables us to relate variations in surface lithology to the frequency and duration of local tidal submergence. Barometric compensation was undertaken on tidal water depth measurements. We undertook near-continuous monitoring of tidal water depths above -1.04 m OD between November 2003 and January 2005.

We installed a groundwater monitoring well in a low marsh setting (surface altitude of +2.26 m OD) to enable us to calculate the maximum effective stress acting on surface sediments due to variations in groundwater level. We hand-augered a 0.1 m diameter borehole into the ground surface to a depth of 2.0 m below ground level (m bgl) and installed a 1.5 m length of slotted PVC well casing within the borehole and plain (non-slotted) well-casing at depths between the ground surface and 0.5 m bgl. We backfilled the space around the well casing with a coarse sand (0.45 – 2.0 m bgl) and bentonite (0.0 – 0.45 m bgl), sealing the base of the well casing with a watertight cap. We installed a self-logging piezometer at known depth below ground level using stretch-proof stainless steel wire and fitted a watertight cap to the well at the ground surface, recording groundwater depths at 5 minute intervals between November 2003 and December 2004.

We determined variations in lithology at the depositional surface by collecting surface sediment samples along a transect from mean sea level to highest astronomical tide level (HAT, 3.25 m OD) at approximately 0.05 m vertical intervals. Surface sediment samples of 100 cm<sup>3</sup> (100 cm<sup>2</sup> by 1 cm deep) were obtained using a sharp knife or trowel, immediately placed in air-

tight bags to prevent moisture loss and were stored in a refrigerator. Sample locations and reference ground levels were levelled to Ordnance Datum Newlyn (m OD) using a Leica TC1010 combined Electronic Distance Measurement (EDM)/theodolite Total Station. We determined organic content by loss on ignition (Heiri *et al.*, 2001). Analysis of particle size was undertaken using laser granulometry following pre-treatment with 20 % hydrogen peroxide to remove fibrous organic matter. Supernatant liquid was decanted before aqueous sodium hexametaphosphate (3.3 wt %), buffered with sodium carbonate (0.7 wt %), was added to the sediment to aid dispersion of flocculated particles. Granulometric analysis was undertaken using a Coulter LS 230 with Polarization Intensity Differential Scattering (PIDS).

We collected multiple, undisturbed, Class 1 block sediment samples (as described by British Standards Institute, 1999) from the upper 0.2 m of the depositional surface at two constant altitudes, one from the tidal flat and the other from a low marsh setting. The block samples were stored in confined, sealed and refrigerated conditions to prevent disturbance due to stress relief, loss of moisture and bacterial decomposition. Physical properties (moisture content, specific gravity, bulk density, Atterberg limits, voids ratios) were determined according to BS 1377 (British Standards Institute, 1990; Head, 1988). Collection of multiple block samples from constant altitudes provided us with ample material to undertake repeat analysis of physical and sedimentological (particle size distribution and organic content) properties. We were therefore able to determine any variability in these properties at each specific sampling altitude. We calculate voids ratios using the Height of Solids method (Head, 1988) and estimate preconsolidation stresses using the graphical construction suggested by Casagrande (1936), which is based on an analysis of the intersection between the recompression line and the virgin compression line.

We undertook standard geotechnical compression testing on sub-samples obtained from the undisturbed block samples using fixed ring, front loading oedometers that, by laterally confining sediment samples (75 mm diameter, 19 mm high), prevent horizontal strains and allow one-dimensional compression, as occurs in undisturbed sedimentary systems (Powrie, 2004). The oedometer specimen preparation, set-up and testing procedure largely follow BS 1377 (British Standards Institute, 1990; Head, 1988). Each new stage of compression involved an approximate doubling of the previous loading pressure (i.e. a load increment ratio,  $\Delta\sigma/\sigma$ , approximately equal to unity). Each loading stage generally lasted 24 hours, though in some tests loading stages were extended (48 or 68 hour loading durations) or truncated to consider the effect of time-dependent creep processes. The results of the extended/truncated creep tests are beyond the scope of this paper and are discussed elsewhere (Brain, 2006). However, such small variations in load increment duration did not alter the compression behaviour of the sediments tested and do not affect the conclusions drawn in this paper (Brain, 2006).

For two samples (LM-6 and MF-6), compression testing was undertaken using a separate apparatus, a back-pressured shear box (BPS). The direct shear capability of the BPS was disabled, allowing one-dimensional compression. Vertical load was applied and measured through the application of an hydraulically-controlled actuator and load cell. Samples (100 mm x 100 mm x 20 mm; width x length x height) were laterally confined. Further details of the BPS equipment and experimental procedure are reported in Brain (2006).

Prior to the application of 26 kPa to individual samples, load increment ratios did not always equal unity. A range of loading scenarios was used in order to constrain preconsolidation stresses more accurately. For each oedometer test, samples were loaded until the maximum compression limit of the oedometer apparatus was reached – i.e. when further downward

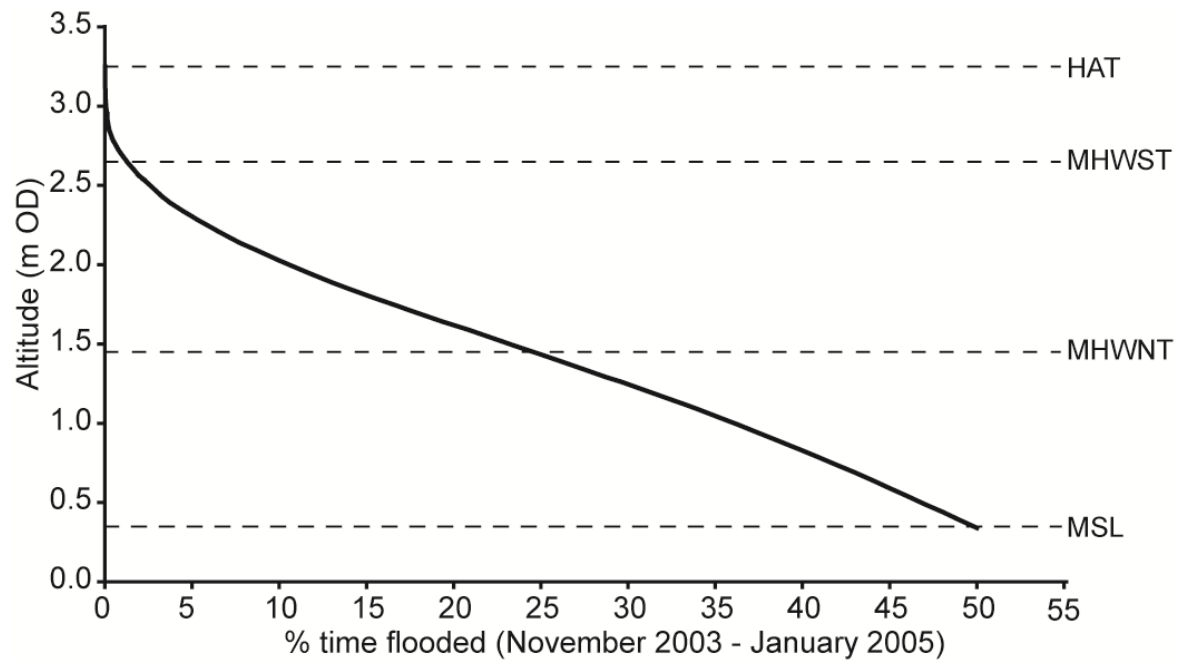
movement of the load hanger was prevented by the fully-lowered screw jack unit. This often occurred prior to the application of the maximum planned load increment stage.

## **5. Results**

### *5.1 Tidal water and groundwater variations*

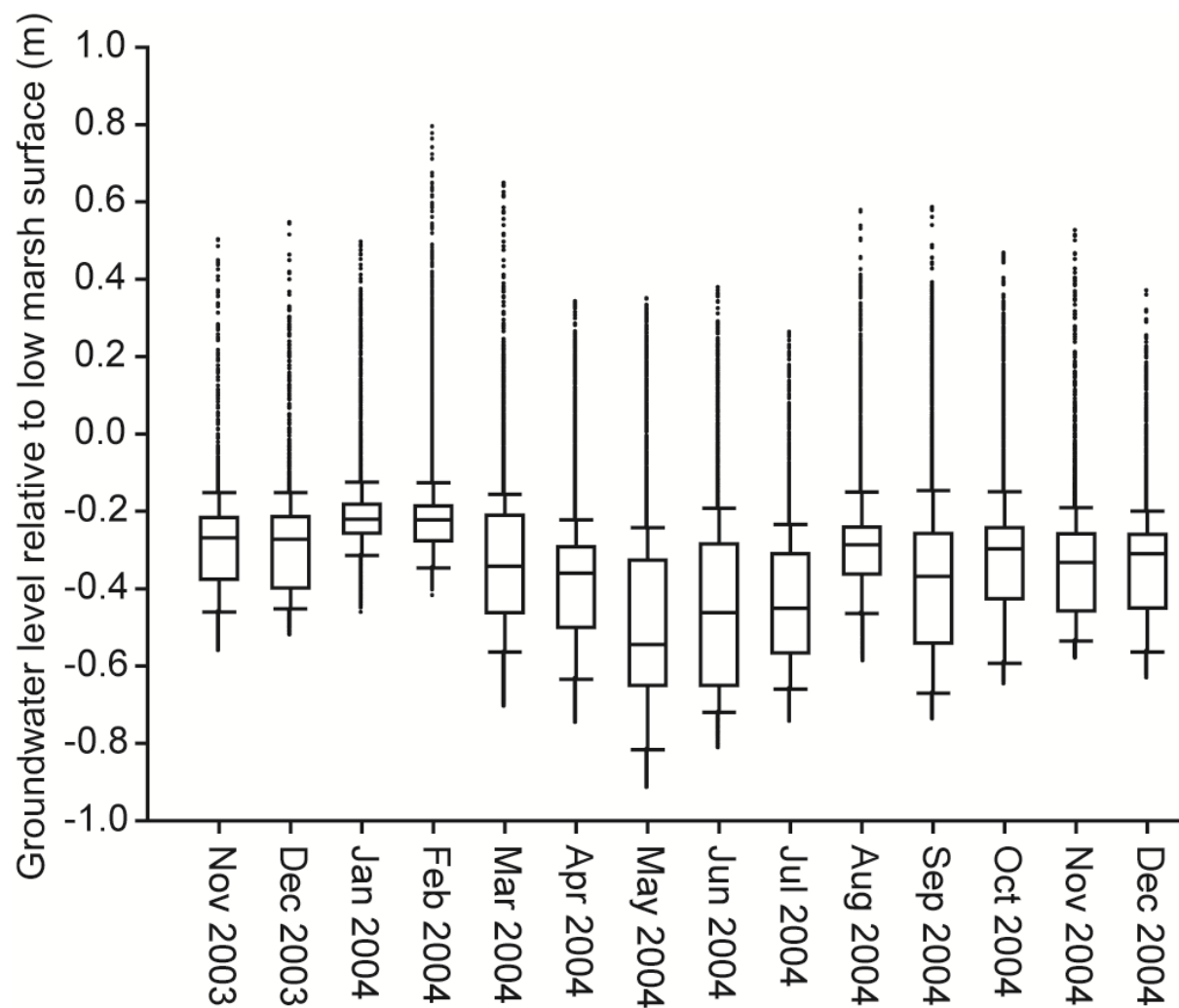
We express the duration of tidal submergence as a percentage of total time monitored (after Gehrels *et al.*, 2001). The relationship between altitude and flooding duration is curvilinear in graphical form (Figure 3). MSL is flooded for 50 % of total time. As altitude increases, this value decreases at a generally constant rate until approximately 2.4 m OD, which is submerged for *c.* 5 % of total time. Above this altitude, and particularly between mean high water spring tide (MHWST) level and HAT level, flooding duration decreases rapidly. At these levels, high in the intertidal frame, the salt marsh surface is rarely submerged (< 2 % of total time, equivalent to brief time periods of less than two hours on one or two tides per month).





**Figure 3** The relationship between flooding duration (expressed as a percentage of total time) and altitude at Greatham Creek.

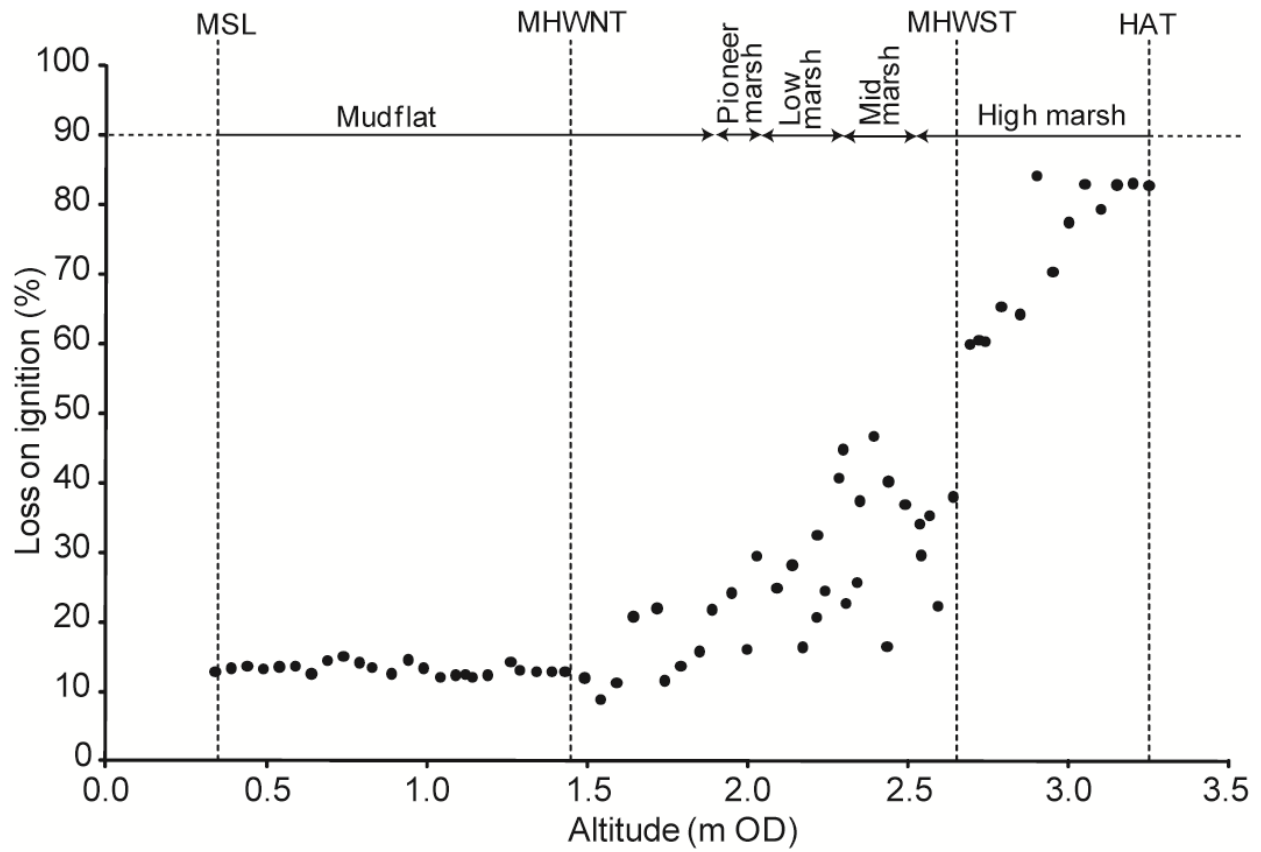
Monthly trends in groundwater variation are displayed in Figure 4. Between the winter months of November 2003 and February 2004, groundwater levels are generally within 0.40 m of the low marsh surface. The warmer weather after this date and a decrease in the quantity and frequency of precipitation resulted in a fall in groundwater levels to a maximum depth 0.92 m beneath the ground surface on May 30<sup>th</sup> 2004. During these periods, the groundwater fluctuated over a larger range of depths than during wetter winter conditions.



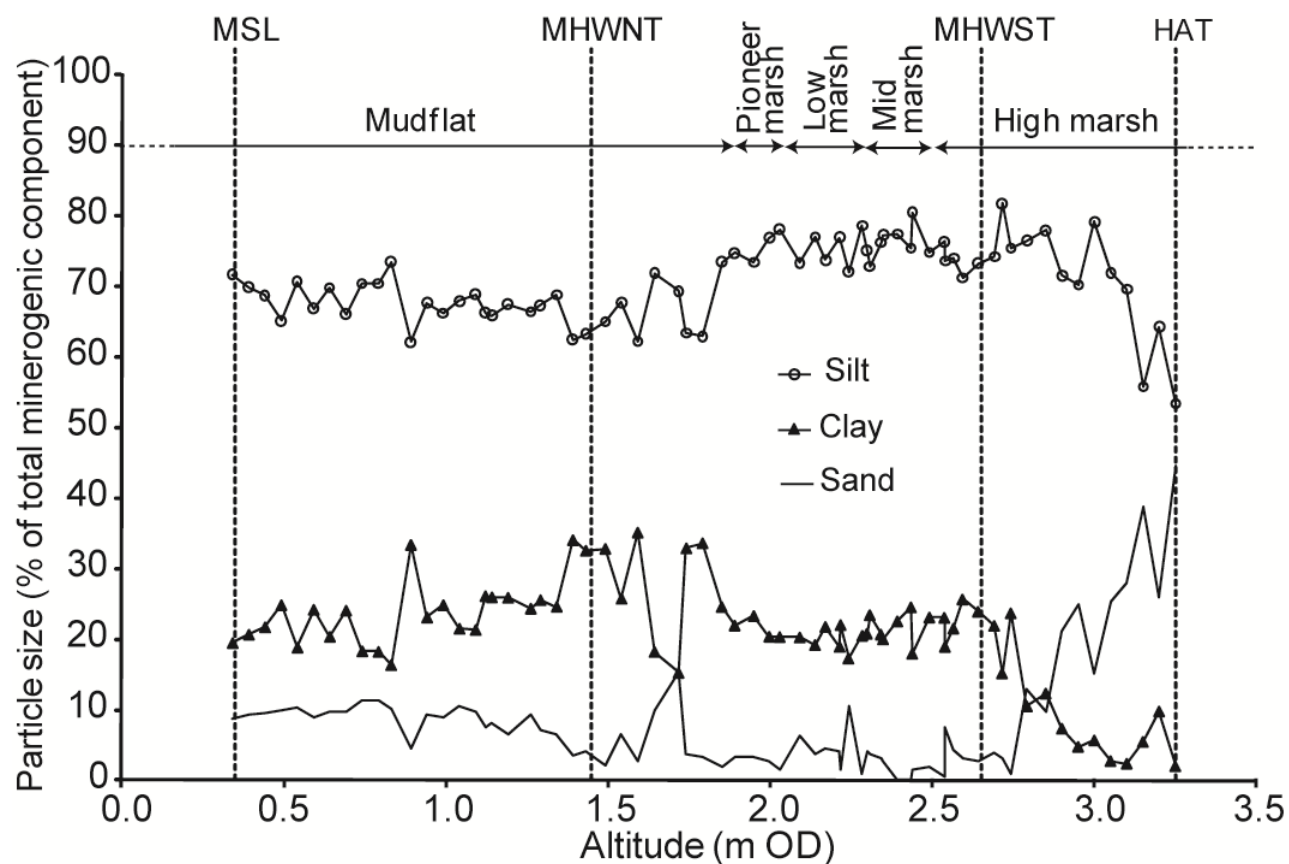
**Figure 4** Boxplots illustrating monthly variations in the depth of the groundwater level in relation to the low marsh depositional surface (0.0 m on the vertical axis). Boxplot ‘tails’ represent 10<sup>th</sup> and 90<sup>th</sup> percentiles. Outliers are represented by individual data points.

## 5.2 *Surface sediments*

From Figures 5 and 6, three broad sediment zones can be identified in the upper intertidal zone at Cowpen Marsh. The first zone coincides with the mudflat, at altitudes between approximately 0.34 m OD and 1.75 m OD. It is characterized by relatively low and constant loss on ignition values of approximately 15 %, a silt content of 65 – 75 %, with variable clay (20 – 35 %) and low sand (< 10 %) contents. The second zone represents the pioneer, low and mid marsh floral environments and lies between *c.* 1.75 and 2.75 m OD. Within this zone, loss on ignition increases from 15 % to 50 %. Silt content ranges between 75 % and 80 %, with clay (*c.* 20 %) and sand (< 5 %) values display less variation. The third zone (2.75 m OD to 3.25 m OD) is indicative of the high marsh floral assemblage. In this zone, loss on ignition increases to 85 %. Sand content increases from < 5 % to 50 %, clay content decreases to < 5% and silt content decreases from 70 % to 50 %. The scatter observed around these general trends and values reflects the transitional nature of marsh floral zones.



**Figure 5** Variations in loss on ignition with altitude. Reference water levels and approximate marsh floral zones are also displayed.



**Figure 6** Variations in silt, clay and sand content with altitude. Reference water levels and approximate marsh floral zones are also displayed.

### *5.3 Material selection*

Sediments in the mudflat, pioneer, low marsh and mid marsh zones have loss on ignition values of  $< 50\%$ . However, pioneer marsh sediments were dry, cracked and friable. Mid marsh sediments consisted of moist, poorly humified vascular plant remains with insufficient minerogenic content to bind the biogenic component. These factors prevented preparation of samples that are suitable for geotechnical compression testing. Hence, two minerogenic sediment sampling locations were selected for testing in this study: low marsh and mudflat. In order to investigate variations in mechanical autocompaction behaviour within each lithology, samples for geotechnical testing were always obtained from the same elevations within the intertidal frame. The mid-points of the altitudinal ranges in which mudflat and low marsh sediments are found were chosen as sampling altitudes. These are the furthest removed from the transitional areas at the edges of each zone and so were taken to be the most representative of each sediment type. Their altitudes are 2.26 m OD (annual flooding duration of *c.* 6 %) for the low marsh samples and 1.06 m OD (annual flooding duration of *c.* 35 %) for the mudflat samples. Our tide gauge data reveal that the mudflat surface (1.06 m OD) is flooded on the majority of tides. Tidal waters did not submerge this altitude during neap tide phases in January, March and September 2004. In contrast, the low marsh surface (2.26 m OD) is generally only flooded on high tides during spring tide phases.

### *5.4 Physical properties*

A description is provided in Table 2 of the mudflat and low marsh sediments using the universal classification scheme proposed by Troels-Smith (1955). The physical properties of the materials and the number of tests undertaken on each sediment type are displayed in Table 3. The two sediment samples are very similar in terms of the minerogenic component. Silt content is essentially equal in the two lithologies (approximately 70 %). The mudflat sediments have a

slightly higher sand content (mean = 15.21 %) than the low marsh sediments (mean = 12.17%). There is also a lower clay content in the mudflat (mean = 12.44 %) than the low marsh (15.81 %) sediments. In contrast, loss on ignition data suggest that the organic content differs more obviously between the two materials. The higher loss on ignition values of the low marsh samples (mean = 24.68 %) reflect *in situ* organic growth and some detrital material. The lower values in the mudflat (mean = 16.83 %) may result from detrital organic and faunal faecal inputs (G. Sills, *personal communication*).



**Table 2** Description of the selected upper intertidal sediments.

<b>Sediment type</b>	<b>Troels-Smith analysis</b>	<b>(1955)</b>	<b>Description</b>
Mudflat	1011-	Ag3As1Ga+Lf+	Very soft, wet, homogeneous, light brown, very slightly sandy, slightly clayey SILT with frequent bioturbation burrows and occasional iron staining. No air pockets visible in the soil structure.
Low Marsh	2021-	Ag2Th2 <sup>1</sup> As+Ga+Sh+Lf+	Soft, moist, brown, very slightly sandy, slightly clayey, organic SILT. Frequent <i>in situ</i> rootlets and partly humified organic matter. Occasional iron staining and streaking. 'Open' soil structure with visible air pockets present.

**Table 3** Physical properties of contemporary low marsh and mudflat samples at Greatham Creek.

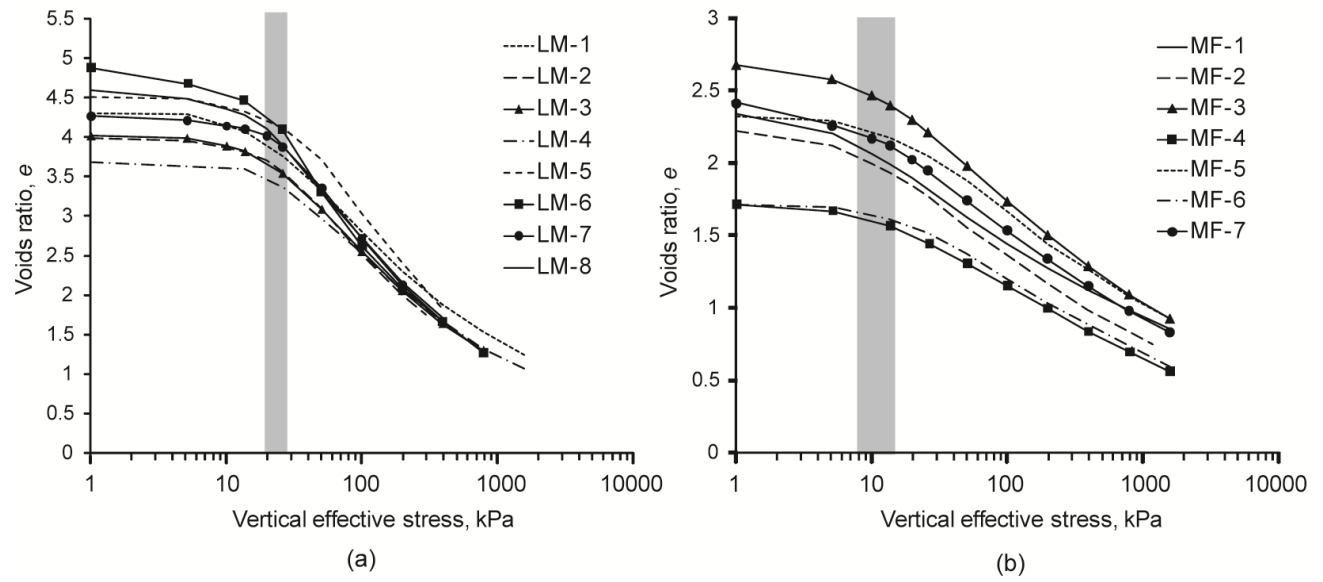
	Low Marsh					Mudflat				
	Mean	Min.	Max.	S.D. <sup>~</sup>	<i>n</i> <sup>*</sup>	Mean	Min.	Max.	S.D. <sup>~</sup>	<i>n</i> <sup>*</sup>
Loss on ignition (%)	24.68	23.45	27.05	1.20	36	16.83	14.11	19.37	1.57	30
Sand (%)	12.17	7.71	15.75	2.54	36	15.21	12.47	18.70	1.75	30
Silt (%)	72.01	68.58	74.78	1.66	36	72.35	69.66	74.62	1.27	30
Clay (%)	15.81	14.14	17.60	1.20	36	12.44	10.11	14.79	1.52	30
Specific gravity, $G_s$	2.48	2.48	2.49	0.00	3	2.63	2.61	2.65	0.02	3
Natural moisture content, $w$ (%)	163.85	137.05	216.34	21.81	36	78.45	61.02	92.88	10.54	30
Liquid limit (%)	96.71	96.59	96.83	0.17	2	48.99	48.79	49.19	0.28	2
Plastic limit (%)	56.31	56.06	56.56	0.00	2	28.94	28.64	29.25	0.43	2
Plasticity index	40.40	-	-	-	1	20.05	-	-	-	1
Initial voids ratio, $e$	4.28	3.69	4.88	0.38	8	2.22	1.71	2.68	0.33	7
Bulk density, $\rho_d$ , at natural moisture content ( $\text{g cm}^{-3}$ )	1.23	1.16	1.27	0.03	8	1.62	1.48	1.42	0.07	7

<sup>~</sup> S.D. = standard deviation.<sup>\*</sup> *n* = number of samples upon which descriptive statistics are based.

Initial voids ratios vary considerably between the two sediment types. The mean initial voids ratio of the low marsh sediment is 4.28. This is more than twice the mean value of the initial voids ratio of the mudflat sediments (2.22). This finding corroborates visual observations that the low marsh sediment displays an obvious ‘open’ structure (Table 2). The low marsh also displays a greater range of initial voids ratios, from a minimum of 3.69 to a maximum of 4.88 (range of 1.19; standard deviation of 0.38). The lower structural variability of the mudflat sediments is illustrated by the smaller range (0.96) and standard deviation (0.33) of initial voids ratios.

### *5.5 Compression behaviour*

$e \log \sigma'$  plots for low marsh and mudflat samples are displayed in Figure 7 and the material properties obtained from these plots in Table 4. All low marsh samples display a consistent pattern of compression behaviour in  $e \log \sigma'$  space. It is also apparent that the material is overconsolidated; the calculated preconsolidation stresses are higher than the existing overburden (0 kPa, since all samples were collected from the depositional surface). Preconsolidation stresses for low marsh materials ranged from 20 kPa to 27 kPa (Table 4). The mean value of  $C_r$  in the low marsh samples is 0.23. For the low marsh samples, the mean value of the compression index,  $C_c$ , is 1.89. This difference in compression indices demonstrates the variation in compressibility at stresses greater and less than the preconsolidation stress.



**Figure 7**  $e$ - $\log \sigma'$  plots displaying one-dimensional compression behaviour of (a) low marsh samples and (b) mudflat samples. Vertical grey bars indicate the range of estimated preconsolidation stresses.

**Table 4** Material and selected physical properties of intertidal samples tested in one-dimensional compression

Sample	$C_r$	$C_c$	$\sigma'_c$ (kPa)	$e_1$	LOI (%)	$w$ (%)
<b>Low marsh samples</b>						
LM-1	0.19	1.44	23	4.30	23.82	147.57
LM-2	0.19	1.71	26	3.98	23.63	155.61
LM-3	0.16	1.54	24	4.02	23.75	151.37
LM-4	0.08	1.41	24	3.69	24.66	137.05
LM-5	0.25	2.12	27	4.51	24.12	170.06
LM-6	0.52	2.27	23	4.88	27.05	182.91
LM-7	0.17	1.92	24	4.26	25.57	162.39
LM-8	0.26	1.88	20	4.60	26.14	172.42
<b>Mean</b>	0.23	1.89	23.88	4.28	24.84	159.92
<b>Standard deviation</b>	0.12	0.43	2.10	0.38	1.27	14.93
<b>Range</b>	0.44	0.86	7	1.19	3.42	45.86
<b>Mudflat samples</b>						
MF-1	0.19	0.57	8	2.34	17.32	83.51
MF-2	0.15	0.62	8	2.22	15.12	79.57
MF-3	0.14	0.73	10	2.68	19.37	92.88
MF-4	0.06	0.50	12	1.71	14.11	61.02
MF-5	0.04	0.63	14	2.32	16.22	80.48
MF-6	0.02	0.52	10	1.86	16.56	69.47
MF-7	0.25	0.64	14	2.41	16.78	88.83
<b>Mean</b>	0.12	0.60	10.86	2.22	16.49	79.39
<b>Standard deviation</b>	0.08	0.08	2.54	0.33	1.67	10.99
<b>Range</b>	0.23	0.23	6	0.97	5.26	31.86

**Key**

$C_r$  = Recompression index

$e_1$  = Initial voids ratio

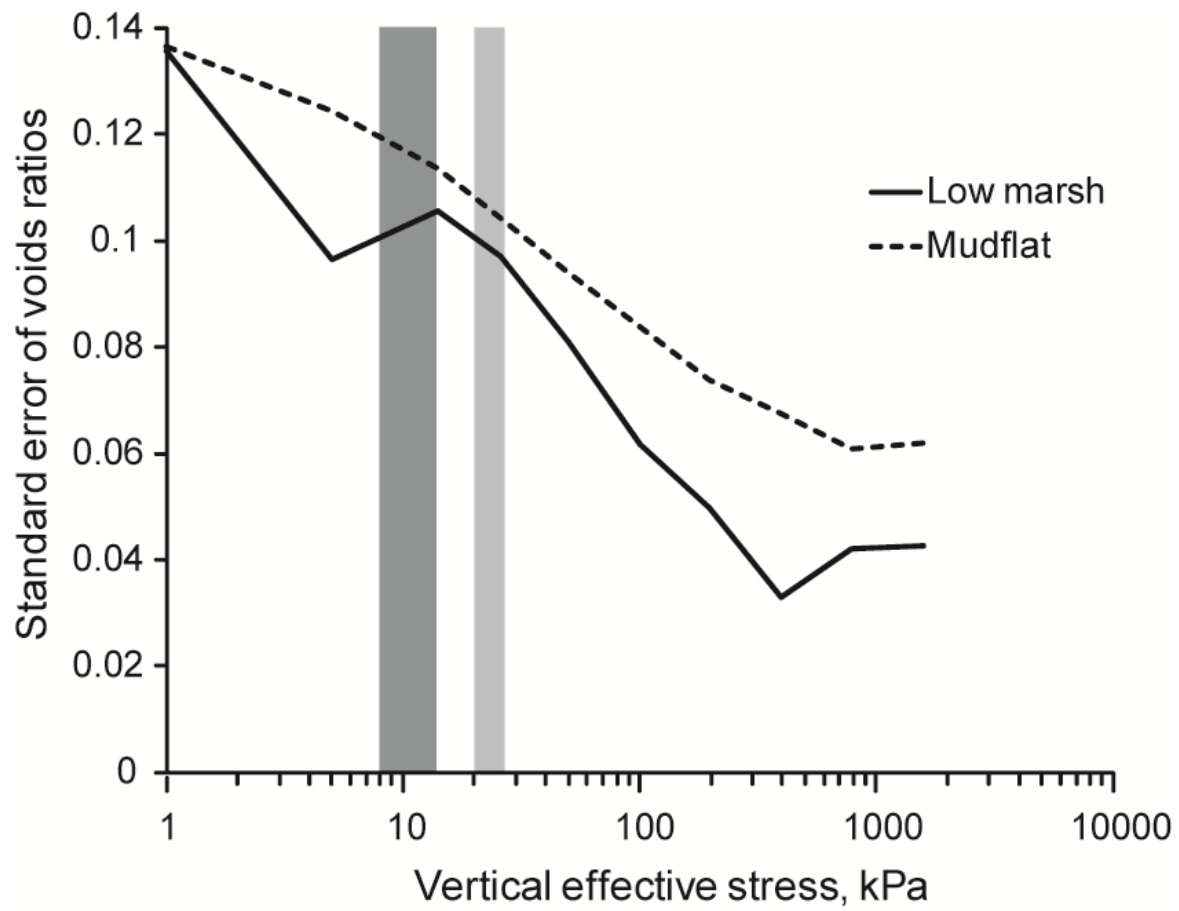
$C_c$  = Compression index

LOI = Loss on ignition

$\sigma'_c$  = Preconsolidation stress  $w$  = Natural moisture content

There is variability in the general trends in compression behaviour of low marsh sediments (Figure 7, Table 4). This is best illustrated by considering the differences in  $C_c$ , which range from a minimum of 1.41 (LM-4) to a maximum of 2.27 (LM-6). Variability also exists for values of  $C_r$ , which range from 0.08 (LM-4) to 0.52 (LM-6). Samples LM-4 and LM-6 also have the minimum (3.69) and maximum (4.88) values of  $e_1$  respectively.

Individual low marsh virgin compression lines are essentially linear in  $e \log \sigma'$  space (Figure 7). However, samples which were subjected to stresses greater than 393 kPa (LM-1, LM-3, LM-4, LM-6) illustrate a slight decrease in the gradient of the virgin compression line at higher stresses, giving the virgin compression line a log-curvilinear form. A convergence of compression lines at higher stresses is evident. This is accompanied by a reduction in the range of voids ratios as effective stress increases. This is further demonstrated in Figure 8, where the standard error of voids ratios is shown to be decreasing as effective stress increases.



**Figure 8** Relationship between the standard error of voids ratios with vertical effective stress. Vertical bars indicate the range of estimated preconsolidation stresses for the low marsh (light grey) and mudflat (dark grey) samples tested.

Low marsh recompression lines are also not wholly log-linear, becoming steeper as the calculated preconsolidation stresses are approached. In addition, the transition from the lower gradient recompression line to the steeper virgin compression line appears to begin at effective stresses less than the range of preconsolidation stresses. The standard error of voids ratios begins to decrease during the recompression phase (Figure 8).

Mudflat samples also show consistent trends in  $e \log \sigma'$  compression behaviour. All samples are overconsolidated and preconsolidation stresses range from 8 to 14 kPa (mean = 10.86 kPa) (Figure 7, Table 4). Recompression gradients (mean  $C_r = 0.12$ ) are less steep than those of the virgin compression line (mean  $C_c = 0.60$ ), signifying differences in compressibility at stresses greater and less than the preconsolidation stress. Variability exists in the compression indices of the mudflat samples (Figure 7, Table 4). The highest observed value of the recompression index,  $C_r$ , (0.25) is from sample MF-7 and the lowest value of  $C_r$  was calculated for sample MF-6. The highest value of  $C_c$  (0.73) was obtained from sample MF-3 which also has the highest initial voids ratio (2.68). The lowest value of  $C_c$  is 0.50 (MF-4), which corresponds with the value of the lowest initial voids ratio (1.71).

Mudflat sediment recompression and virgin compression lines are generally log-linear, though as observed in the low marsh sediments, the recompression line begins to steepen before preconsolidation stresses are reached. Also, the gradients of individual virgin compression lines start to decrease at higher effective stresses, notably in samples MF-1, MF-2, MF-3, MF-5 and MF-7. Compression lines converge at as effective stresses increase, though this trend is less pronounced than in the low marsh sediments. The standard error of voids ratios decreases at a largely constant rate at effective stresses less than *c.* 800 kPa.



## 6. Discussion

### 6.1 Initial structural variability

All low marsh samples were obtained from constant altitude (2.26 m OD) and displayed minor variations in lithological properties. The mudflat samples, again collected from fixed altitude (1.06 m OD), also displayed only small variations in lithological parameters. However, considerable structural variability was observed within each sediment type and between the low marsh and tidal flat samples.

The higher loss on ignition values in the low marsh sediment (mean loss on ignition value of 24.58 %, compared to 16.82 % in the mudflat sediments analysed) reflect the presence of vascular plants which are known to create well-aerated, highly porous soil structures (Delaune *et al.*, 1994) that may be more prone to compression. In addition, the lower flow velocities on the salt marsh (Leonard and Luther, 1995; Möller *et al.*, 1999; Christiansen *et al.*, 2000) during tidal flooding leads to slow deposition and an open random fabric (Burland, 1990). Sediment trapping by vegetation (Alizai and McManus, 1980; French and Spencer, 1993) and biofilms (Austen *et al.*, 1999) and the subsequent flaking of silt-rich crusts (Allen, 2000) may also assist in the creation of an initial open soil structure. In contrast, the absence of *in situ* vascular vegetation growth on the mudflat surface precludes the formation of an organogenic openly structured fabric. Initially denser structures are created by more rapid deposition rates from a denser suspension (Been, 1980; Been and Sills, 1981; Burland, 1990; Sills, 1998; Lintern, 2003). This results in a more compact, oriented soil fabric and lower initial voids ratios (Burland, 1990).

Within-sample variations in initial structure are likely to result from minor variations in depositional conditions. Spatial and temporal variations in water chemistry, flow velocity and the density of sediment in tidal waters will cause differences in floc size and soil structure. In

addition, in the low marsh environment, variations in plant species assemblage and canopy height may result in variations in flow velocities, creating differences in settling style and sedimentation rate. Plater *et al.* (1998), for example, demonstrate both spatial and temporal (downcore) variations in sedimentation rate at Cowpen Marsh using radionuclides.

## 6.2 Overconsolidation

One-dimensional compression testing of low marsh and mudflat materials obtained from the intertidal zone at Cowpen Marsh demonstrates that both the low marsh and mudflat are overconsolidated, and to different degrees. It is reasonable to infer that the observed overconsolidation is caused by variations arising from the tidal cycle and associated groundwater level changes, which together expose surface and near-surface sediments to a range of subaerial and vadose zone conditions and processes.

We make first-order approximations of the influence of groundwater falls on effective stresses acting on surface sediments using standard soil mechanics and theory. In hydrostatic situations, pore water pressures decrease above the water table at a rate of  $9.81 \text{ kPa m}^{-1}$  (Powrie, 2004). This increases effective stress without an increase in total stress (Equation 1). The maximum observed groundwater depth below the low marsh surface was 0.92 m (May 30<sup>th</sup> 2004). Using hydrostatic principles, the effective stress acting on surface sediments as a result of this groundwater fall was approximately 9 kPa. This would have caused a calculated preconsolidation stress in the low marsh materials of 9 kPa. The greater preconsolidation stresses estimated from the oedometer test results are likely to have resulted from a more complex interaction of desiccating processes and the soil moisture demands of vegetation, both of which create negative pore water pressure (soil suction) (Marinho and Chandler, 1993; Wilson *et al.*, 1997; Mathur, 1999). The presence of vascular plants in the low marsh sediment also

aerates the soil and enhances the withdrawal of moisture from soil interstices *via* evapotranspiration and evaporation (Powrie, 2004). The effects of such processes are demonstrated by the work of Smethurst *et al.* (2006), who installed a network of piezometers and tensiometers at a cut-slope, vegetated by rough grass, herbs and small shrubs, in the London Clay at Newbury, Berkshire, UK. They reported maximum summer soil suction values of between *c.* 50 kPa at 1.0 m depth and *c.* 450 kPa at 0.3 m depth. They attribute this to a soil moisture deficit caused by vegetation suction. It is reasonable to assume that similar processes operate within salt marshes. However, soil moisture deficits and hence suction stresses are likely to be lower in coastal sediments as a result of tidal inundation on at least a monthly basis and a generally higher coastal groundwater table.

Variations in preconsolidation stress between the low marsh and mudflat sediments are likely to result from the lower flooding duration of the low marsh sampling site (6 % of total time, as opposed to 35 % of total time at the mudflat sampling site). This increases the duration of exposure to desiccating subaerial processes and reduces the opportunity for soil moisture contents to be recharged. Similarly, the vegetated salt marsh surface increases the potential for soil moisture deficits and negative pore water pressures. Within-material variability in preconsolidation stress results from small-scale spatial and temporal differences in effective stress acting at the depositional surface. Prior burial by sediment and subsequent erosion of this overburden is an additional potential cause of the overconsolidation observed in the sediments obtained from the depositional surface at Greatham Creek. No obvious lithostratigraphic evidence of erosion, such as sharp lithostratigraphic contacts, was observed within the upper 0.3 m of the stratigraphy at our sampling locations (Brain, 2006). Whilst this alone does not preclude erosion as the mechanism, basic geotechnical analysis further suggests that erosion

cannot be the sole cause of the observed overconsolidation. It is possible to calculate the approximate thickness of eroded overburden sediments that would have caused the observed preconsolidation stresses in the sediments at the depositional surface, the lowest of which was 8 kPa in the mudflat material. If the hypothetical eroded overburden sediments were composed of a saturated sand (uniform bulk density of  $2 \text{ g cm}^{-3}$ ), and assuming hydrostatic conditions and dissipation of all excess pore water pressures, a preconsolidation stress of 8 kPa would have been effected in the sediments immediately beneath the erosion surface by 0.8 m of eroded overburden. If buried by a less dense material obtained from the intertidal zone (e.g. bulk density of  $1.44 \text{ g cm}^{-3}$ ), a preconsolidation stress of 8 kPa would have been effected in the sediments by removal of approximately 1.85 m of overlying material. Using the maximum estimate of late twentieth century sedimentation rates calculated for Cowpen Marsh by Plater *et al.* (1998) ( $22.67 \text{ mm yr}^{-1}$ ), deposition of even 0.8 m of overburden sediment would have taken approximately 30 years. Hence, the sediments at the current depositional surface that display overconsolidation would be expected to display a minimum age of 30 years if erosion of overlying sediments of sufficient thickness to cause even the minimum preconsolidation stresses had occurred. Plater *et al.* (1998) develop radionuclide chronologies for shallow (*c.* 0.2 – 0.3 m) sediment cores obtained from the mudflat and salt marsh environments at Cowpen Marsh. These chronologies demonstrate that the uppermost 0.1 – 0.2 m of the stratigraphic column accumulated within the past 30 years. Hence, the sediments at the contemporary depositional surface are recent and so erosion of large thicknesses ( $\geq 0.8 \text{ m}$ ) of overburden is highly unlikely to have occurred. Despite radionuclide evidence of erosion at some locations at Cowpen Marsh by Plater and Ableby (2004), the erosion depths involved appear to be relatively shallow ( $< 0.1 \text{ m}$ ) and so this erosion cannot account for the preconsolidation stresses observed within the

sediments at Greatham Creek, particularly given the cautious nature of the values used in our calculations (i.e. lowest preconsolidation stresses, highest sedimentation rates and hence minimum thicknesses of hypothetically eroded sediments).

### *6.3 Compressibility and destructure*

Mean values of all compression indices for the low marsh ( $C_r = 0.23$ ,  $C_c = 1.89$ ) are higher than those of the mudflat ( $C_r = 0.12$ ,  $C_c = 0.60$ ), indicating higher compressibility (more than three times greater during virgin compression) of the low marsh sediments. The general higher compressibility of the low marsh materials is likely to be related to the higher levels of organic material in the soil in comparison with mudflat sediments (Delaune *et al.*, 1994). The more open initial structure of the low marsh sediments is more prone to volumetric reduction in response to loading than the initially denser mudflat materials (after Burland, 1990).

Similar intralithology relationships are evident. Strong, statistically significant correlations exist between  $e_1$  and both  $C_c$  and  $C_r$  in the low marsh; and between  $e_1$  and  $C_c$  in the mudflat (Table 5). These generally strong, positive and statistically significant correlations further suggest that sediments with more open initial structures are more susceptible to compression at effective stresses less than and greater than the preconsolidation stress. Since minor variations in  $e_1$  are likely to be controlled by small variations in the depositional environments (Section 6.1), changes in structure and compression behaviour through space at the depositional surface translate into rapid stratigraphic variations in compressibility within a sedimentary sequence.

**Table 5** Correlations between initial voids ratios and compression indices of low marsh and mudflat samples tested for compression behaviour.

			<b>Low Marsh</b>		<b>Mudflat</b>	
			Compression index, $C_c$	Recompression index, $C_r$	Compression index, $C_c$	Recompression index, $C_r$
Initial ratio, $e_1$	voids	$r$	<b>0.823</b>	<b>0.879</b>	<b>0.936</b>	0.598
		$p$	<b>0.012</b>	<b>0.004</b>	<b>0.002</b>	0.157

$r$  = Pearson's correlation coefficient,  $p$  = significance (two-tailed). Significant correlations are in bold type.

These relationships help to explain the observed convergence of the virgin compression lines, a phenomenon previously noted by Schofield and Wroth (1968), Skempton (1970), Burland (1990) and Tovey and Paul (2002), and also reductions in structural variability observed at higher stresses. Samples with denser initial structures are less compressible both pre- and post-yield as they are structurally more stable and closer to the ‘intrinsic’ (i.e. independent of depositional structures) state of the material (Burland, 1990). Less dense samples are highly structured relative to the intrinsic properties of the material; such structures result from the variations in depositional conditions and lithological characteristics discussed above. Application of an effective stress to sediments with initially open fabrics begins to break down the sedimentary structures in a ‘destruction’ process (Leroueil *et al.*, 1979; Burland, 1990).

With increased application of effective stress, destruction removes the influence of depositional conditions and causes increased homogeneity of compression behaviour, as indicated by the convergence of compression lines, and structure, as indicated by decreases in the standard errors of voids ratios with increasing effective stress (Figure 8). In both low marsh and mudflat sediments, the effects of destruction are less pronounced at effective stresses greater than *c.* 800 kPa, when the standard error of voids ratios remains largely stable (Figure 8).

#### *6.4 Limitations of Virgin Compression Models*

Our basic one-dimensional compression tests reveal important differences in compression behaviour from those described by the VCM. We now explore the implications of our findings for use of the VCM when predicting volume changes in minerogenic intertidal sediments.

Variations in voids ratio at the depositional surface occur in both low marsh and mudflat sediments. This violates an assumption of VCMs that intra-lithology variability in structure does not exist and that a deterministic approach is valid. Single values of initial voids ratio used in

VCMs are unlikely to adequately describe the range of structures observed at the depositional surface.

The oedometer compression testing shows that both the low marsh and mudflat sediments are overconsolidated and that each lithology displays a range of calculated preconsolidation stresses. Again, this challenges an assumption of VCMs that sediments are normally consolidated. The VCM, involving a backwards extrapolation of the virgin compression line to 1 kPa, provides an inadequate representation of the one-dimensional compression behaviour of minerogenic intertidal sediments at stresses less than the preconsolidation stress. Hence, use of the VCM to predict the past compression behaviour of minerogenic sediments, using *in situ* material properties, would overestimate voids ratios (and hence volumes and layer thicknesses) at effective stresses less than the preconsolidation stress.

Characterisation of the physical properties of the low marsh and mudflat materials reveals little variation in their lithology. Despite this, compression testing shows that both low marsh and mudflat samples display variations in compression behaviour. Values of the key compression indices ( $C_c$  and  $C_r$ ) vary between samples of the same lithology. This demonstrates that the compression behaviour of an apparently uniform lithological unit cannot adequately be described by single values of the compression indices. This contrasts with the assumption of the VCM that there is no intra-lithology variability in compressibility and that a deterministic approach is therefore valid.

These points challenge the validity of applying a single value of the compression index to a geotechnically variable, although lithologically uniform, material. The implications become evident when considered in relation to existing approaches. Current procedures to predict volume change in intertidal sediments begin by splitting a stratigraphic column into a number of



layers, within which the geotechnical and lithological properties are assumed to be constant (Paul and Barras, 1998; Pizzuto and Schwendt, 1997; Tovey and Paul, 2002; Massey *et al.*, 2006). The ideal situation would involve obtaining one-dimensional compression test and voids ratio measurements at the highest possible resolution; 0.02 m, for instance, to allow an oedometer test to be undertaken on the material. Such an approach is impractical given the time that would be required to test at this resolution throughout even a short (e.g. 1 metre) core. Instead, it has been common practice to obtain a value of the compression index for an arbitrarily defined stratigraphic layer based on a single oedometer or liquid limit test and then apply this value to the entire unit. Due to the observed variation in the compression behaviour in surface sediments, such an approach would appear to be inadequate, since rapid downcore variation in compressibility is likely to take place in apparently homogenous lithologies.

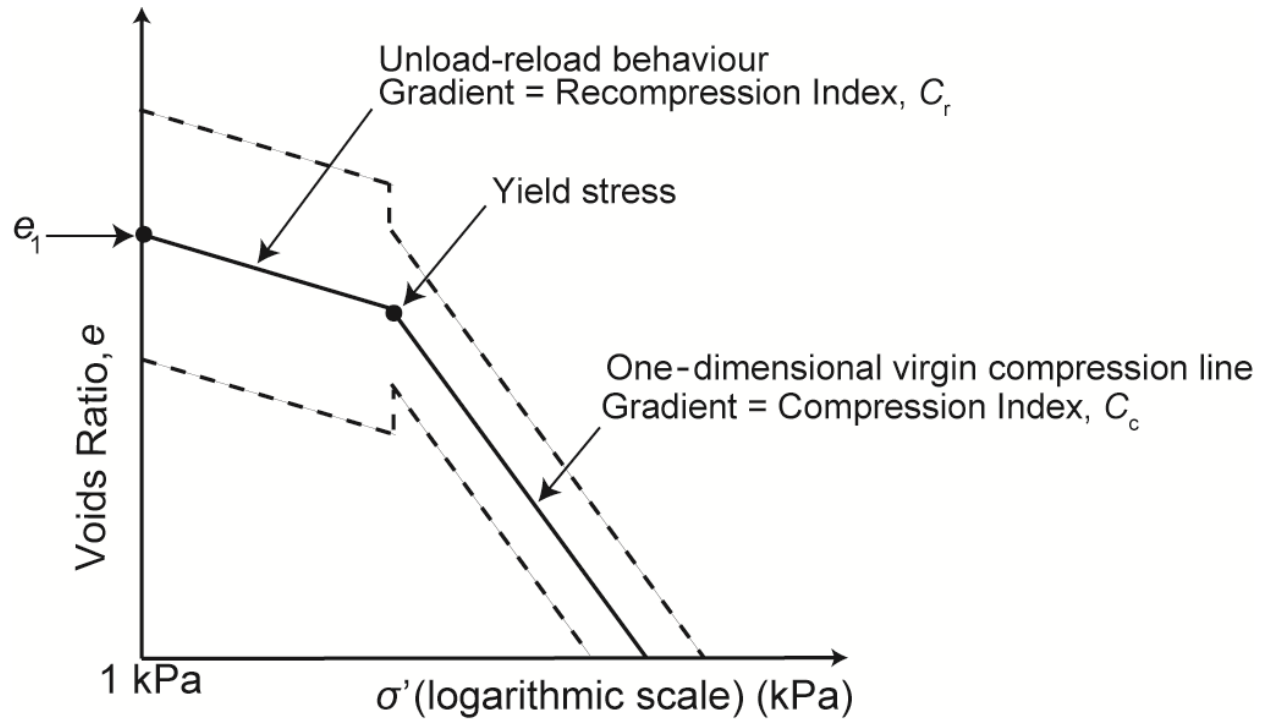
The observed destructuration in intertidal sediments creates further problems when estimating historical compression behaviour and volumetric change for decompaction procedures. Convergence of virgin compression lines and the removal of depositional structures limits the use of oedometer tests undertaken on samples obtained from depth in predicting previous compression behaviour and volumetric conditions. Due to the increased homogeneity of structure and compression behaviour at higher stresses, ‘memory’ of the previous compression behaviour and depositional structures and volume is lost. A simple backwards extrapolation of the virgin compression line based on *in situ* properties would not permit prediction of the initial structural variations that are subsequently lost upon increased exposure to vertical effective stress. This would potentially lead to over- or under-estimations of layer thicknesses at low effective stresses.

### 6.5 A new framework for modelling compression in minerogenic intertidal sediments

On the basis of our findings, VCMs do not adequately describe compression behaviour in minerogenic intertidal sediments. Our results allow us to make informed decisions to develop a framework that more accurately describes the volumetric evolution of minerogenic intertidal sediments.

The  $e \log \sigma'$  framework remains sufficient for describing compression behaviour in response to variations in effective stress, but with the some modifications to the VCM. To account for the observed overconsolidation at the depositional surface, both the recompression line and the virgin compression line must be described in the conceptual framework. A value of the initial voids ratio is also required; this relates to the intercept of the recompression line rather than the intercept of the virgin compression line. It was noted in Section 5.5 that the transition from the low gradient, overconsolidated recompression line to the steeper gradient virgin compression line begins to occur at an effective stress lower than the preconsolidation stress. We therefore distinguish between the preconsolidation stress and the yield stress. We use the latter to describe the effective stress at which soil stiffness decreases as compression behaviour begins to move from the recompression line to the virgin compression line. It represents the point at which structural resistance to compression begins to break down (Nash *et al.*, 1992). Importantly, we consider the yield stress to be related to the actual compression behaviour of the soil and so is of greater use in describing compression behaviour than estimations of the preconsolidation stress. Finally, a statistical approach model is required that is capable of describing variations and uncertainty in initial ( $e_1$ ) and post-yield structure (voids ratio), yield stress and pre- and post-yield compression behaviours ( $C_r$  and  $C_c$ ). Our proposed conceptual framework to describe compression behaviour in minerogenic intertidal sediments is illustrated

in Figure 9. A more detailed description of model development is beyond the scope of this paper, as are model application and validation. Such work is ongoing.



**Figure 9** Components of the proposed conceptual framework to describe compression behaviour. Dashed lines indicate error margins that incorporate variations in structure and compression behaviour at effective stresses less than and greater than the yield stress. A decrease in the vertical range of the error margins at effective stresses greater than the yield stress represents the loss of depositional structure and resistance to compression at and following yield.

The conceptual framework describes the compression behaviour of minerogenic intertidal sediments in response to increases in effective stress. It only describes the volumetric effects of the consolidation process, during which overburden total stresses are transferred from pore water to the soil skeleton over time and hence increasing effective stresses. The framework does not describe the time element of the consolidation process that results from variable hydraulic conductivity and drainage paths (see Price, 2009, for example). Similarly, time-dependent creep processes that typically operate as consolidation ends (i.e. at constant effective stress) are assumed to be negligible but warrant further investigation. An additional assumption of our conceptual description of compression behaviour is that post-depositional diagenetic changes in chemical composition of the sediment do not occur. Such changes would result in increased bulk density and compressive strength *via* interparticle cementation (Tovey and Yim, 2002).

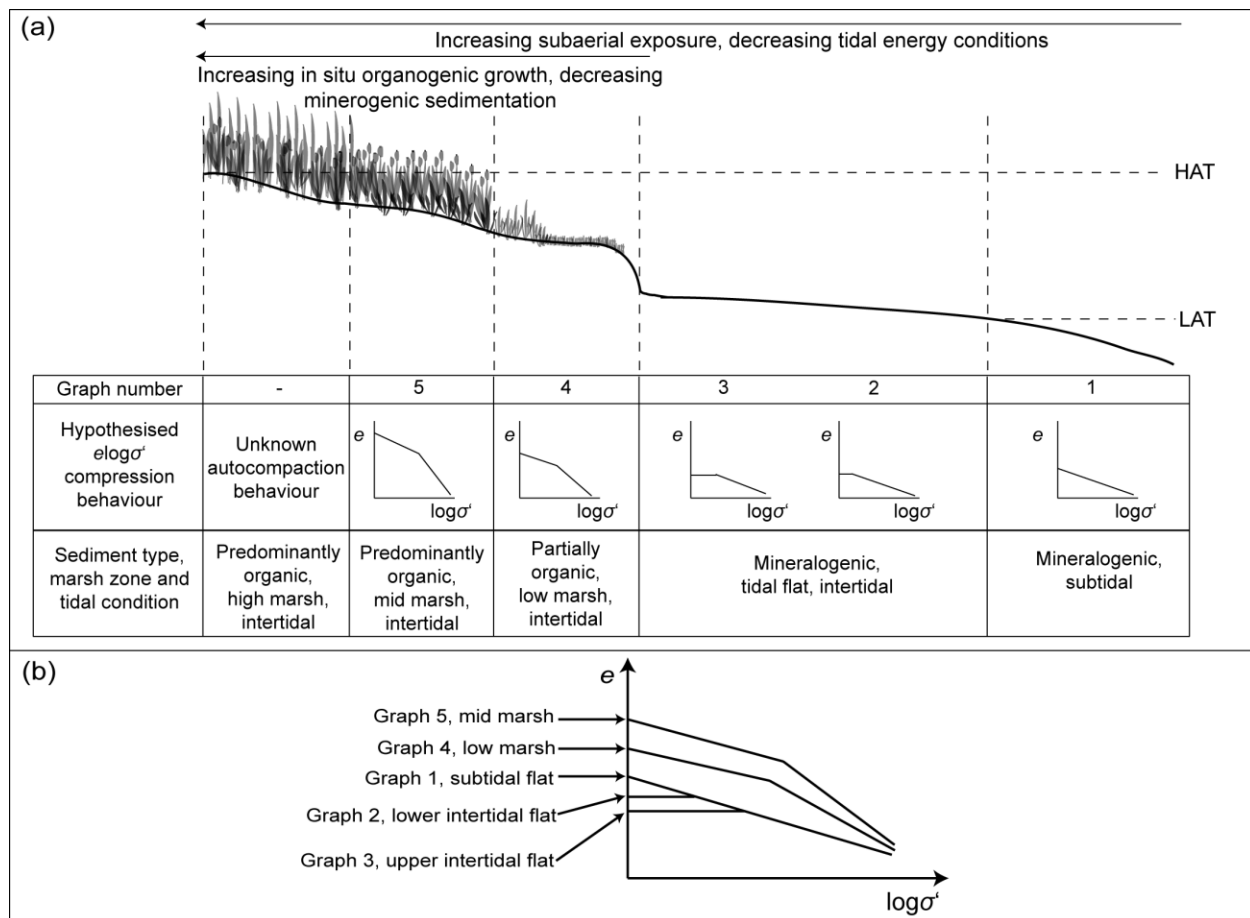
#### *6.6 Model transferability*

Before the conceptual framework developed above can be applied to minerogenic intertidal sediments at different locations, particularly when hindcasting the compression behaviour of fossil sediments, it is important to demonstrate that the processes that determine the key model parameters are universal, rather than simply relating to a specific set of samples obtained from Cowpen Marsh. Sections 6.1 - 6.3 describe the likely lithological and environmental controls on each of the components of the conceptual compression framework (Figure 9). Given the granulometric similarity of the mudflat and low marsh samples and the observed differences in loss on ignition,  $e_1$ ,  $C_r$  and  $C_c$  between the two lithologies, organic content appears to exert a strong control on the initial structure and compressibility of soils. The organic content of low energy intertidal sediments is controlled by relative elevation and, hence, flooding duration and frequency, which partly control the vertical zonation of salt marsh

vegetation (Silvestri *et al.*, 2005). Overconsolidation results from the operation of the tidal cycle and the consequent subaerial exposure and groundwater water level falls. In turn, these phenomena allow desiccation to occur and create capillary suction stresses, causing soil moisture deficits and resultant additional vegetation suction stresses. These overconsolidating processes control the preconsolidation and yield stresses in intertidal sediments.

Importantly, all model parameters are related, either directly or indirectly, to the operation of the tidal cycle and the associated processes summarised above. Variations in values of the model parameters ( $e_1$ ,  $C_r$  and  $C_c$  and the yield stress) can be expected to occur within a given intertidal zone with specific sedimentological, ecological, geomorphic and hydrographic conditions. At subtidal levels, where the environment is considerably less dynamic and where subaerial exposure and groundwater variations do not occur by definition, the lower end member of the continuum exists. Overconsolidation is unlikely here and so the compression behaviour in  $e \log \sigma'$  space can be described by a standard VCM (Figure 10, Graph 1). Within the fully minerogenic section of the intertidal zone, similar materials form but their compression behaviour is modified by subaerial desiccation and groundwater variations. Hence, with increased elevation above LAT, the yield stress can be expected to increase (Figure 10, Graphs 2 and 3). In the partially organic low marsh environment, the *in situ* production of organic matter leads to an increase in  $e_1$  which, in turn, results in greater values of  $C_r$  and  $C_c$ . Furthermore, the greater frequency and duration of subaerial exposure increases the yield stress (Figure 10, Graph 4). In mid marsh environments, where minerogenic sedimentation still contributes to lithological composition, it is possible that the material property continuum continues, with higher organic contents creating more open, compression prone structures (higher initial voids ratios and compression indices) and increased subaerial exposure yield stresses resulting in greater yield

stresses (Figure 10, Graph 5). However, towards the higher elevations within the intertidal zone, the applicability of the proposed modelling framework is uncertain due to higher organic contents (Figure 10) and the associated variations in autocompaction processes.



**Figure 10** Hypothetical variations in the general compression behaviour of sediments at varying elevations within a typical NW European salt marsh: (a) variations in compression behaviour in relation to environmental conditions and controls (schematic diagram not to scale); (b) summary and comparison of varying compression behaviours.



Since the controlling processes are common to all low energy intertidal environments, the conceptual compression model here is considered to be applicable to other minerogenic sediments forming in low energy intertidal areas. However, parameters obtained from one specific intertidal area may not be directly transferable to others. Varying hydrographic and geomorphic settings and local sedimentological, ecological, geochemical and climatic conditions are likely to influence the specific values of the compression framework parameters.

Zong and Horton (1999) present details of the sedimentological characteristics of six UK low energy coastal sites representing different tidal ranges (meso- to macro-tidal) and geomorphic settings (estuarine, embayment and lagoonal). The sedimentological characteristics of the six sites vary. For example, sand content in the tidal flat environments at Roudsea Marsh, Morecombe Bay (macrotidal, estuarine), Thornham Marsh, Norfolk (macrotidal, lagoonal) and Tramaig Bay, Jura (microtidal, embayment) range from 50 – 100 % (Zong and Horton, 1999). Vegetation cover (%) and species composition varies within and between sites (see Table 2 of Zong and Horton, 1999). Similarly, loss on ignition varies between sites, from the low values ( $\leq c. 30\%$  at all elevations) observed in the Nith Estuary, Solway Firth (macrotidal, estuarine) to the highly organic substrate of the Kentra Bay site in Argyll (mesotidal, embayment) where loss on ignition values range from  $> 50\%$  in the low marsh to  $100\%$  in the high marsh. The effect of these variations in sediment composition and character are likely to influence initial structural characteristics ( $e_1$ ) and subsequent compression behaviour ( $C_c$  and  $C_r$ ). In addition, variations in granulometric characteristics may influence the operation of autocompaction processes, since coarser sediments with pore sizes and configurations more conducive to rapid drainage may experience more enhanced drying than sediments containing greater proportions of silts and clays. However, the overconsolidating effects of drying may be more pronounced in cohesive

sediments that can experience greater suction stresses during desiccation (cf. Hawkins, 1984; Marinho and Chandler, 1993). Further research is required to determine the significance of varying granulometric and organic composition on values of initial structural characteristics (see Bird *et al.*, 2004; Bartholdy *et al.*, 2010), preconsolidation stresses and compression indices.

Additional sedimentological and geochemical factors may also affect compression behaviour and values of each of the framework parameters. Under suitable reduction-oxidation (redox) conditions, variations in local sediment composition and pore water chemistry can result in the concentration of redox-sensitive compounds and geochemical zonation (Cundy and Croudace, 1995; 1996; van Huissteden and van de Plassche, 1998; Thomson *et al.*, 2002). The enrichment of redox sensitive elements can result in point contact cementation (Hawkins, 1984) in sediments at the depositional surface (i.e. syn-depositional enrichment and cementation). This may result in lower initial voids ratios and compression indices and greater yield stresses, reflected in increased structural resistance to compression (cf. Nygard *et al.*, 2004; Gutierrez and Wangen, 2005).

Variations in tidal range may lead to changes in the degree of overconsolidation experienced at different elevations. In larger estuarine systems, such as that of the Severn (extreme hypertidal range of 14.8 m; Allen, 2000), overconsolidation towards HAT may increase due to prolonged desiccation during summer neap tides and as groundwater levels fall (Hawkins, 1984; see also Crooks, 1999; Barras and Paul, 2000). In contrast, a smaller tidal range may result in a lesser degree of overconsolidation since surface sediments are likely to be in closer proximity to tidal water and groundwater, allowing continued saturation of the near-surface sediments *via* tidal flooding and capillary action. More pronounced overconsolidation will lead to greater preconsolidation and yield stresses. Variations in yield stress are also likely to result

from local climatic factors, such as mean and extreme temperatures and precipitation patterns, which have the potential to lower or raise groundwater levels and, hence, desiccate or moisten intertidal sediments (cf. Greensmith and Tucker, 1971; Greensmith and Tucker, 1986).

In larger minerogenic sedimentary systems such as the Ganges – Brahmaputra delta, India/Bangladesh, South Asia, sedimentation rates are significantly higher than those generally observed in contemporary UK saltmarshes as a result of rapid tectonically-driven relative sea level rise (Goodbred and Kuehl, 2000). Here, Allison and Kepple (2001) obtain a recent sedimentation rate of  $11 \text{ mm yr}^{-1}$  on the basis of  $^{137}\text{Cs}$  dating. It is possible that these high sedimentation rates reduce the opportunity for drying during neap tides and warm periods. As a result, the degree of overconsolidation may be lower, since deposited sediments are buried before they can dry out and undergo the associated effective stress increases.

Given this potential for variation in values of the compression framework parameters as a result of varying local ecological, sedimentological, geochemical, climatic, geomorphic and hydrographic conditions, there is evidently a requirement to obtain site-specific values of  $e_1$ ,  $C_r$  and  $C_c$  and the yield stress using laboratory geotechnical testing. Each lithology in a given intertidal zone has its own distinctive initial structure and subsequent compression behaviour. Providing that the sediments considered are primarily minerogenic, the framework to describe compression behaviour presented in Section 6.5 should remain applicable. A larger database of material and physical properties from a greater range of elevation from different sites would allow this hypothesis to be tested.

## **7. Conclusions**

This paper addresses the autocompaction behaviour of recently deposited minerogenic sediments by presenting, for the first time, a suite of geotechnical experiments designed to test

fundamental assumptions that underpin existing geotechnical autocompaction models. Our main conclusions are as follows:

1. Low marsh and mudflat samples display inter- and intra-lithology variability in structure (voids ratio), both at the depositional surface and as compression proceeds. These variations are largely due to differences in organic content and salt marsh root content.
2. All low marsh and mudflat materials are overconsolidated to varying degrees. Low marsh samples analysed have been subjected to effective stresses in the range 20 – 27 kPa prior to the commencement of burial. In the mudflat samples, preconsolidation stresses range from 8 – 14 kPa. We argue that the observed overconsolidation results from desiccation and capillary suction stresses caused by varying degrees of subaerial exposure, falls in groundwater level and the moisture requirements of vascular plants.
3. Variations in compression behaviour occur both within and between lithologies. Samples with higher initial voids ratios, and hence more open and unstable initial structures, are more compressible than samples with initially denser structures (lower voids ratios).
4. Structural variability decreases with application of higher effective stresses due the operation of destructuration processes that remove influence and ‘memory’ of initial structure and result in increased homogeneity of compression behaviour at higher effective stresses.
5. We contend that the Virgin Compression Model provides an inadequate description of the one-dimensional compression behaviour of minerogenic intertidal soils. Without modification on the basis of our findings, the VCM is likely to overpredict layer thicknesses at effective stresses less than the yield stress. In addition, destructuration prevents accurate estimation of the range of structures and, hence, layer thicknesses that occur at lower values of effective stress if *in situ* conditions are used as the basis of such estimates.

6. We address the deficiencies of VCMs by developing a new conceptual framework that describes overconsolidation. We recommend the use of a statistical model to account for structural variability. We argue that the model parameters are controlled by factors common to all low energy intertidal environments, namely flooding frequency and duration and associated ecological zonation. We therefore suggest that the conceptual framework is broadly applicable to minerogenic intertidal sediments at different locations and burial depths within Holocene stratigraphic sequences. However, site-specific measurements of the constituent framework parameters are required to account for local variations in ecological, sedimentological, geochemical, climatic, geomorphic and hydrographic conditions. Hence, the individual characteristics of different field locations should be carefully considered before the suggested framework is routinely applied.

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